Radial Localization of Alfven Eigenmodes and Zonal Field Generation

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Outlines

- Motivation
- Linear AE physics
- Nonlinear AE physics
- Discussions & Summary

✓ ***Energetic particle (EP) transport by Alfven eigenmode (AE) can degrade confinement of burning plasmas***

✓ ***This paper reports gyrokinetic particle simulation of AE excited by EP in DIII-D tokamak***

Gyrokinetic Turbulence Simulation of EP Transport

- **Fully self-consistent simulation of energetic particle (EP) turbulence and transport must**
  - **Incorporate kinetic effects of thermal particles at micro-scale**
  - **Treat EP and thermal plasmas on the same footing (non-perturbative)**

- **Large dynamical ranges of spatial-temporal processes require simulation codes efficient in utilizing peta-scale computers**

- **Therefore, studies of EP physics in ITER burning plasmas call for a new approach of global nonlinear gyrokinetic simulation**

- **US DOE SciDAC GSEP (Gyrokinetic Simulation of Energetic Particle Turbulence and Transport)**

- **Verification & Validation: RSAE frequency up-sweeping and mode structures from gyrokinetic simulations agree well with DIII-D experiments (shot # 142111) [*D. A. Spong et al, PoP2012*]**

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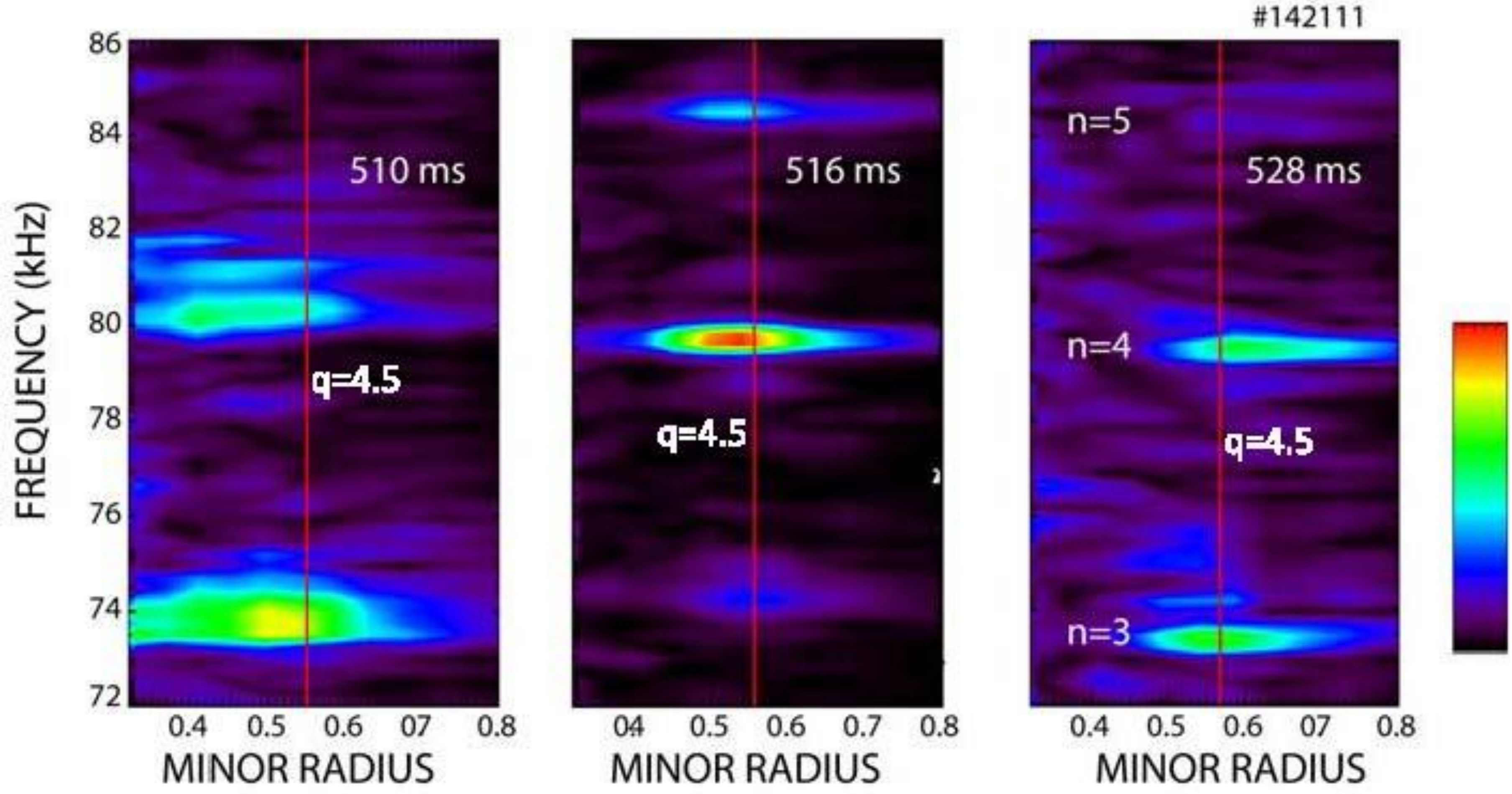
✓ ***Linear physics: What is EP effects on AE dispersion relation and mode structure?***

✓ ***Gyrokinetic simulations with kinetic effects of thermal plasmas and non-perturbative EP effects recover experimental results of toroidal Alfven eigenmode (TAE) in DIII-D***

✓ ***Non-perturbative EP effects induce TAE radial localization***

Measurement Shows Fast Radial Drift of TAE in DIII-D

- TAE moves rapidly while thermal plasma profiles barely change
- Cannot be explained by perturbative theory: thermal plasma profiles set MHD mode structure, EP only drives growth rate

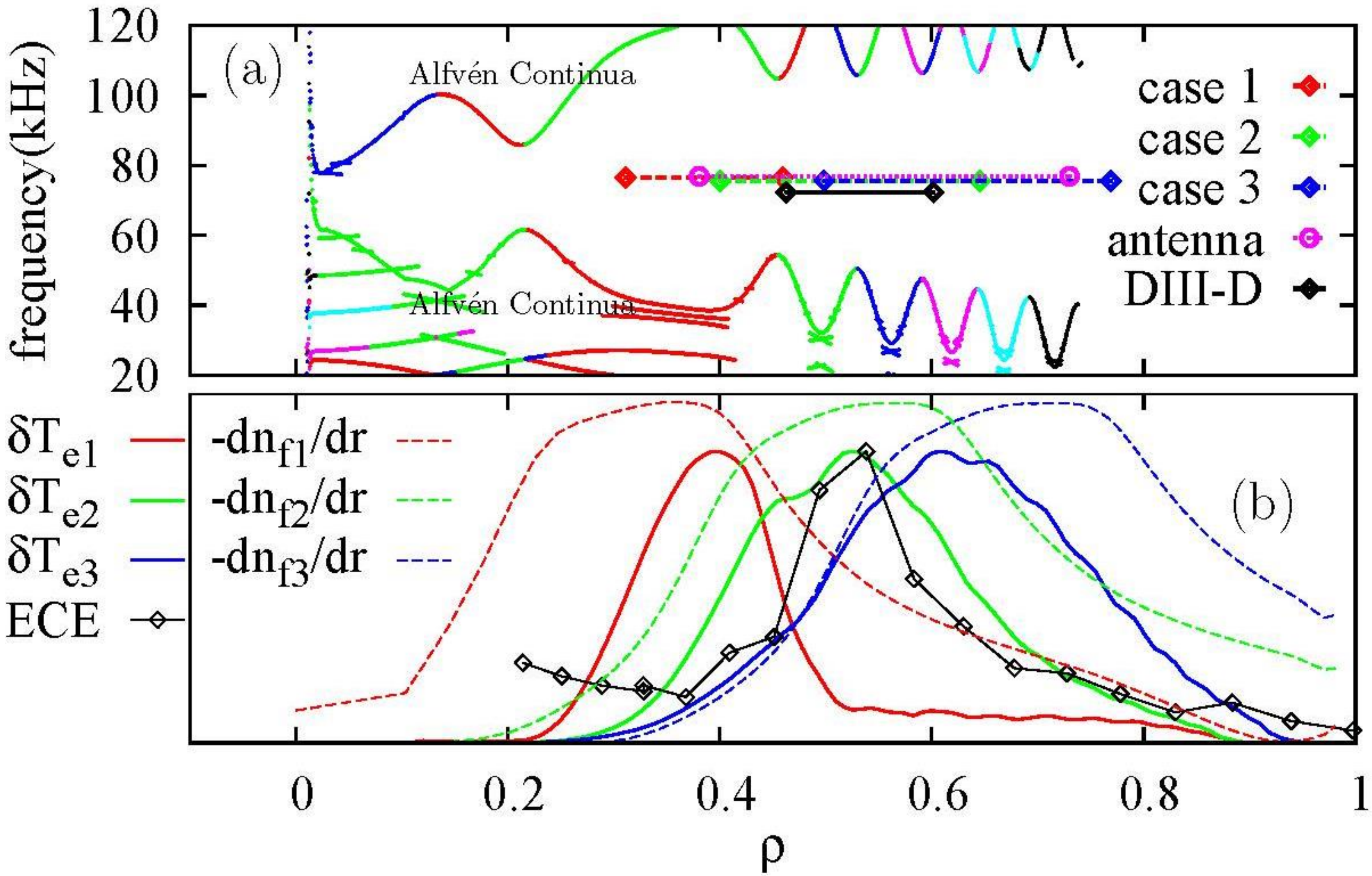


TAE in DIII-D shot # 142111 around 525ms

GTC Simulations Find TAE Radial Localization

- Simulations scan EP profiles within experimental uncertainty
- Unstable TAE radial structures move with EP density gradient
- In contrast, stable TAE excited by antenna has larger radial width
- EP non-perturbative contribution induces TAE radial localization

TAE in DIII-D shot # 142111 at 525ms

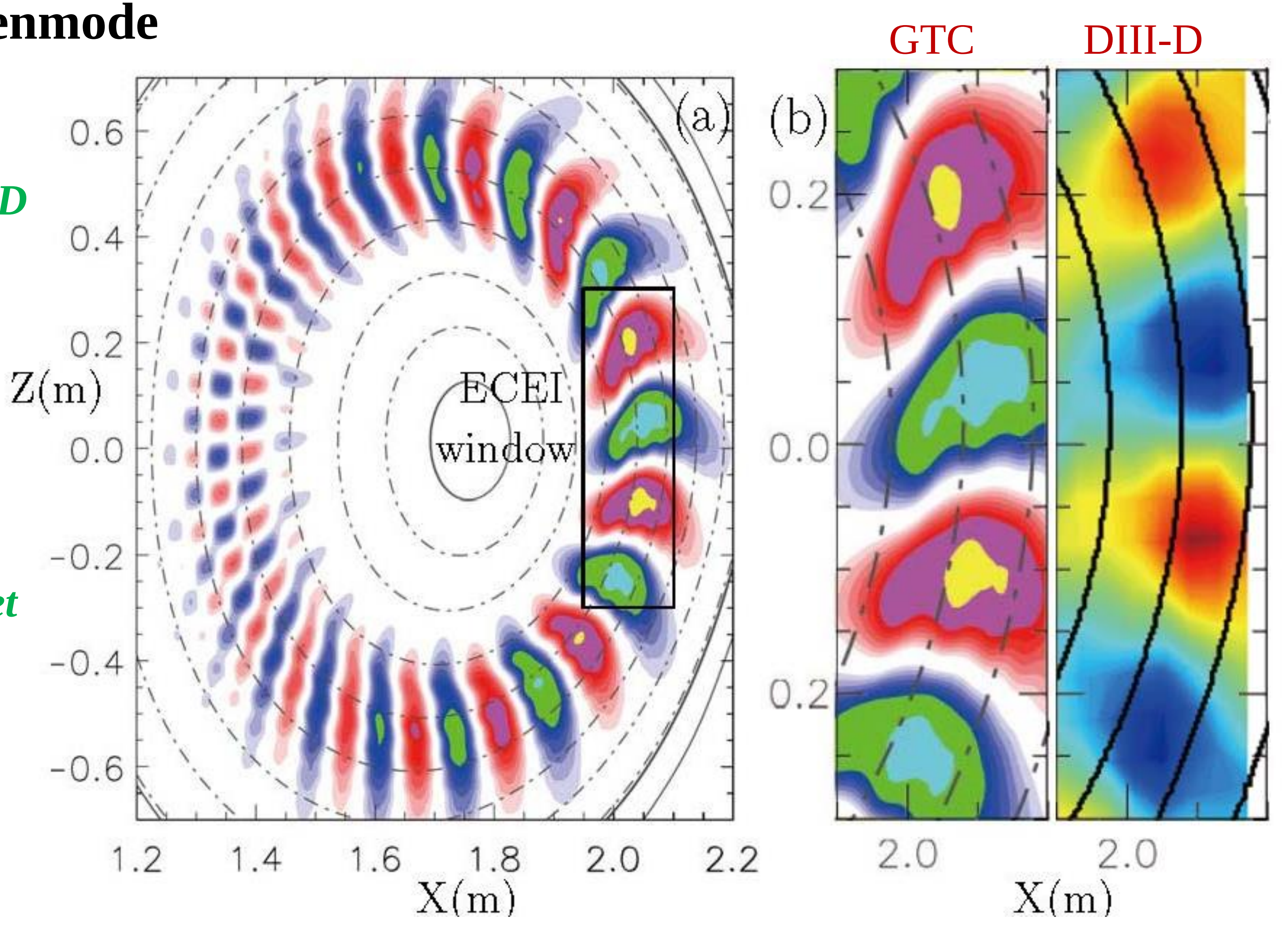


Comparison of TAE Mode Structures between Simulation & Experiment

- **EP non-perturbative contribution breaks radial symmetry of TAE eigenmode**

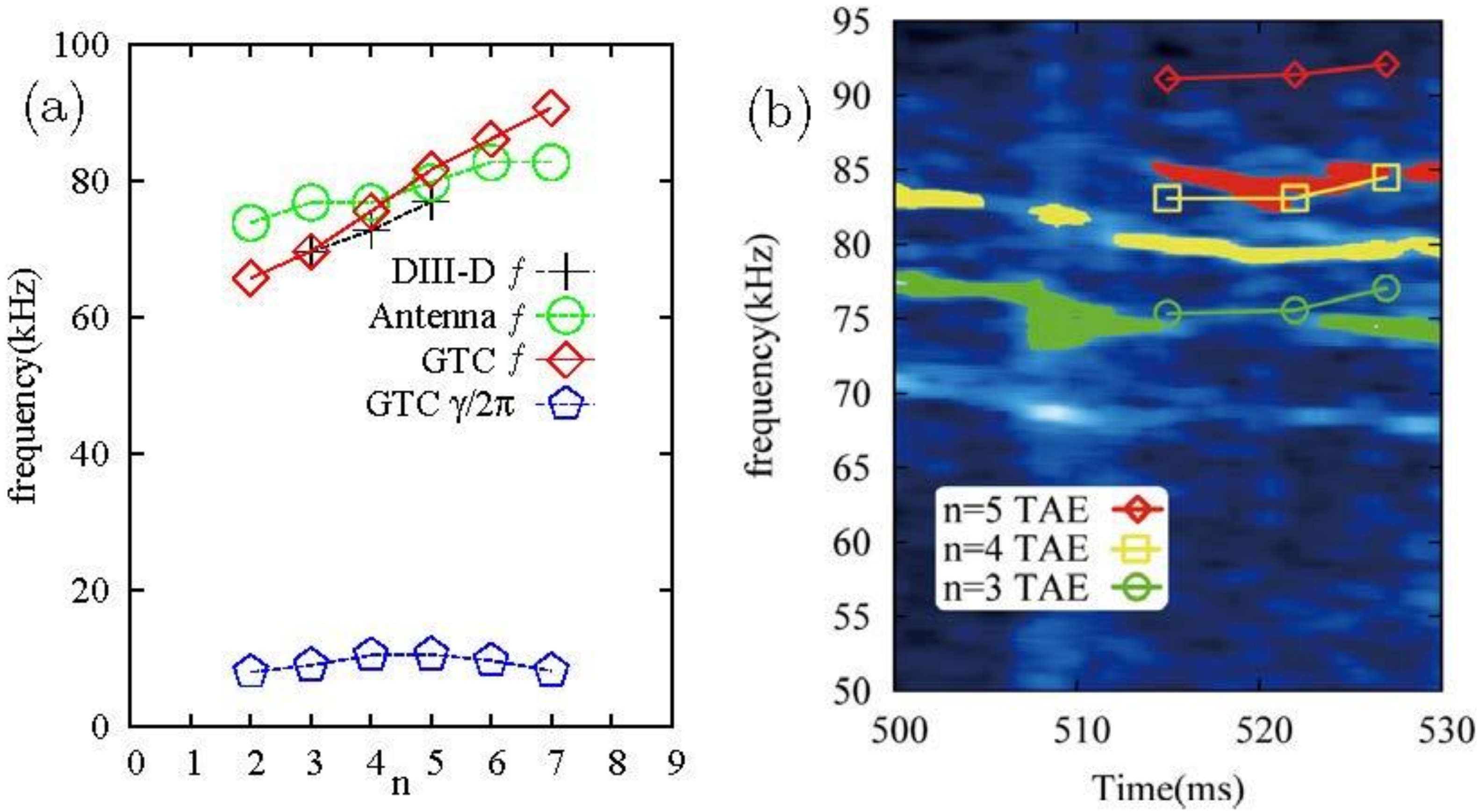
TAE in DIII-D shot # 142111 at 525ms

[Z. X. Wang et al, PRL2013]



Comparison of TAE Frequency between Simulation & Experiment

- **EP non-perturbative contribution and trapped electron effects induce TAE frequency dependence on toroidal mode number n**



TAE in DIII-D shot # 142111 at 525ms

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✓ ***Nonlinear physics: How does AE saturate? What is NL dynamics***

✓ ***Conventional model: Perturbative theory and reduction of dimensionality from 3D to 1D, i.e., single toroidal mode, radially local***

✓ ***Non-perturbative simulation: Nonlinear physics beyond 1D model***

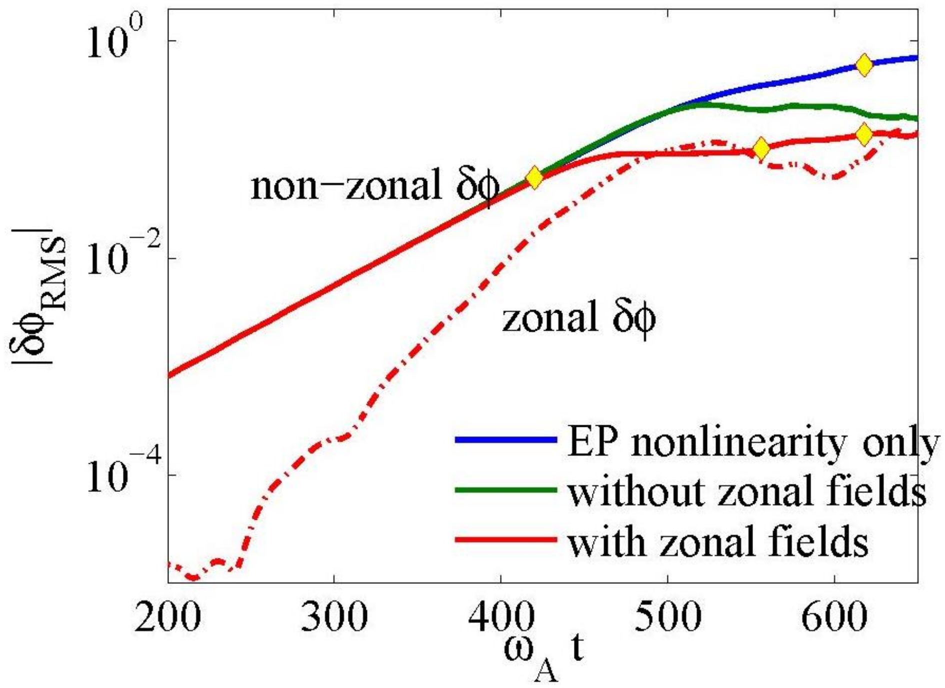
- ***Zonal fields (flow & current) generated by AE nonlinear mode coupling***
- ***Fast frequency chirping induced by radial variations of AE mode amplitude & guiding center dynamics***

GTC Simulations Find TAE Saturation by Zonal Flow

- **Suppressing zonal flow: higher TAE saturation amplitude**
- **Removing thermal particle nonlinearity: even higher TAE amplitude and relaxation of EP profiles**
- **TAE saturates by zonal flow without relaxation of EP profiles**
- **Zonal current has little effects on TAE saturation**
- **γ_{ZF}~$1.9\gamma_{TAE}$: zonal fields generated by TAE nonlinear mode coupling, not modulational instability**

Nonlinear simulation of TAE in DIII-D shot # 142111 at 525ms

[Z. X. Wang, PhD Thesis, 2014]

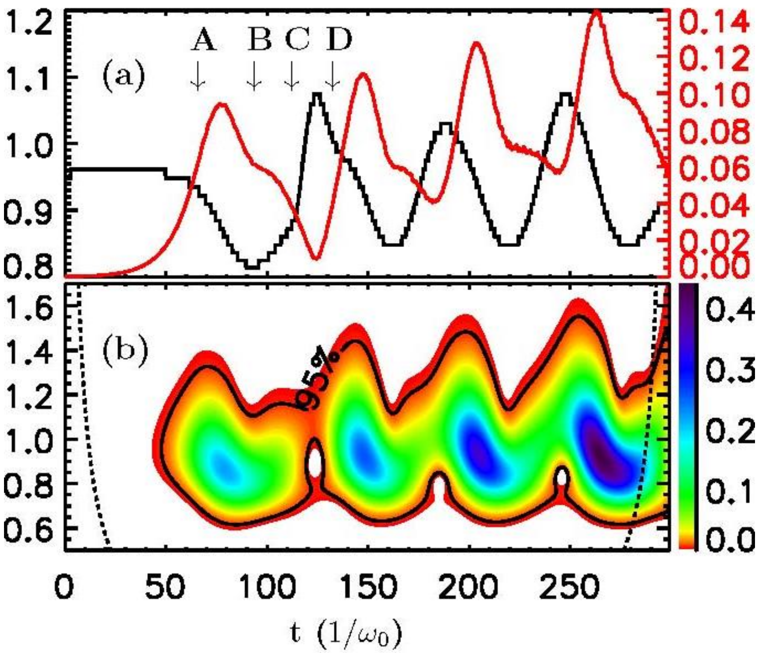


Generation of Zonal Flow by Alfven Eigenmode

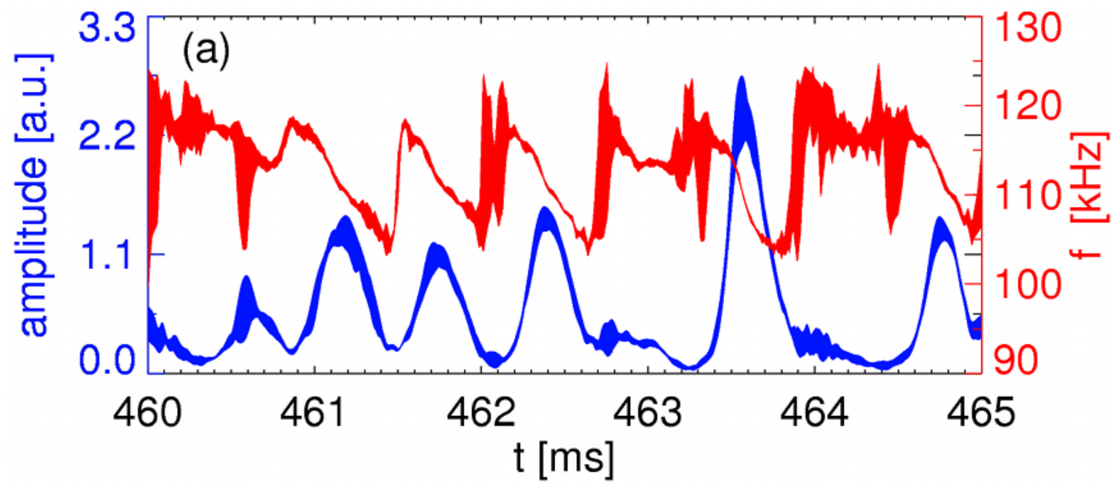
- **Zonal flow generation by driftwave vs. Alfven eigenmode**
  - **Driftwave: modulational instability**
  - **AE: nonlinear mode coupling**
- **Electrostatic vs. Electromagnetic turbulence**
  - **Electromagnetic: Stochastic magnetic fields could suppress zonal flow generation because of increase of zonal flow dielectric constant due to electron adiabatic responses, i.e., electron shielding effects**
  - **No similar effects in electrostatic turbulence**
- **Conjecture: Stochastic magnetic fields of RMP (resonant magnetic perturbation) could suppress zonal flow generation, and lead to enhanced driftwave turbulence in H-mode pedestal; Need to be tested by gyrokinetic simulation with 3D RMP fields**

GTC Nonlinear Simulations of BAE Find Fast Chirping

- Fast, repetitive, mostly downward chirping
- 90º phase shift between intensity and frequency oscillations
- Simulation consistent with recent NSTX TAE, ASDEX BAE
- Chirping mechanisms: nonlinear formation vs. destruction of phase space island due to radial variations of mode structure & guiding center dynamics (intrinsically 2D dynamics)



[H. S. Zhang et al, PRL2012]



[M. Podesta et al, NF2011; PPPL-4719]

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✓ ***AE is an example of MHD modes with kinetic effects in fusion plasma excited by pressure gradients or equilibrium currents***

✓ ***Gyrokinetic simulation of kinetic-MHD processes:***

- ***MHD mode frequency < ion cyclotron frequency***
- ***kinetic effects important in MHD modes***

Gyrokinetic Simulation of Kinetic-MHD

- **Macroscopic MHD modes limit burning plasma performance and threaten fusion device integrity: NTM, RWM, sawtooth etc**
- **Kinetic effects at microscopic (thermal particles) & meso-scales (EP) and coupling of multiple processes play a crucial role in excitation and evolution macroscopic MHD modes**
- **Neoclassical tearing modes (NTM): set principal performance limit in both ITER baseline and hybrid scenarios**
- **Predictive NTM simulation needs to incorporate kinetic physics at multiple spatial and temporal scales:**
  - ✓ **microturbulence**
  - ✓ **neoclassical bootstrap current**
  - ✓ **magnetic island dynamics (current driven MHD instability)**
- **Gyrokinetic toroidal code (GTC) simulation of kinetic-MHD: first-principles, integrated simulation of nonlinear interaction between microturbulence, EP, MHD, & neoclassical transport**

Gyrokinetic Toroidal Code (GTC)

- **GTC current capability for kinetic-MHD simulation:**
  - **General 3D toroidal geometry & experimental profiles**
  - **Microturbulence & EP: Kinetic electrons & electromagnetic fluctuations**
  - **MHD: Equilibrium current, resistive and collisionless tearing modes**
  - **Neoclassical transport**
  - **RF: fully kinetic ions**
  - **Ported to GPU (titan) & MIC (tianhe-2)**

[Z. Lin et al, Science1998]

http://phoenix.ps.uci.edu/GTC

- **Other GTC papers at this meeting:**
  - ✓ **Microturbulence: TH/P2-44, Y. Xiao,** ***Gyrokinetic Simulation of Microturbulence in EAST Tokamak and DIII-D Tokamak***
  - ✓ **EP: TH/P7-29, W. L. Zhang,** ***Verification and Validation of Gyrokinetic Particle Simulation of Fast Electron Driven Beta-Induced Alfven Eigenmode on HL-2A Tokamak***
  - ✓ **MHD: TH/P4-11, I. Holod,** ***Global Gyrokinetic Simulations of Electromagnetic Instabilities in Tokamak Plasmas***
  - ✓ **RF: TH/P2-10, A. Kuley,** ***Nonlinear Particle Simulation of Radio Frequency Waves in Fusion Plasmas***

Summary

- **Linear physics: Gyrokinetic particle simulations find radial localization of toroidal Alfven eigenmodes in DIII-D tokamak due to non-perturbative contribution by energetic particles**
- **Nonlinear physics: Gyrokinetic particle simulations find**
  - **Nonlinear saturation of toroidal Alfven eigenmodes by zonal flow, which is generated by TAE mode coupling**
  - **Nonlinear chirping of beta-induced Alfven eigenmode due to radial variations of mode amplitude and guiding center dynamics**
- **Future work: EP transport, coupling to MHD modes**

GSEP project webpage http://phoenix.ps.uci.edu/gsep